ARMY RESEARCH LABORATORY

Design of the Stop Plate and Stop Bolt for the Uniport

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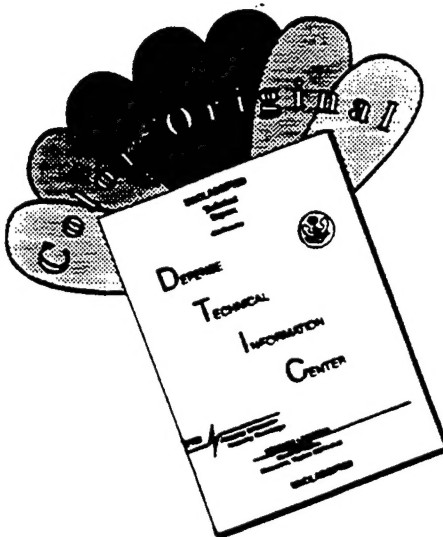
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Abstract

This report has two main purposes. The first is to document the problems with the previous system for limiting rotation of the Uniport. The second purpose is to document the design of the new system to limit rotation of the Uniport. (The Uniport consists of a unicycle type mobility platform, which allows a person to "pedal" his or her way through the virtual environment.) The previous system for limiting rotation consisted of a steel cable attached to a support structure at one end and bolted to the turntable at the other end. This system suffered from two main problems. The moment arm for the bolt holding the cable was so long that it created large stresses in the bolt, which caused it to fail by fatigue. The other main problem was that the cable twisted and kinked, which caused some of the strands of the cable to break. The new system for limiting rotation has been designed to resist fatigue failure and failure from impact loading. The stop plate and stop bolt provide an effective and reliable means to limit rotation of the Uniport.

ACKNOWLEDGMENTS

CONTENTS

DESIGN OF THE STOP PLATE AND STOP BOLT FOR THE UNIPORT

INTRODUCTION

Reason for Developing the Uniport

In 1994, Sarcos Research Corporation, under a contract with the Human Research and Engineering Directorate of the U.S. Army Research Laboratory, built the Uniport. (The Uniport consists of a unicycle type mobility platform, which allows a person to "pedal" his or her way through the virtual environment.) The Uniport was built as a proof-of-concept device to allow individual infantry soldiers to participate in distributed interactive simulations with aircraft and armored vehicle simulators. Previously, such simulators only existed for airplanes, helicopters, and armored vehicles but not for individual infantry soldiers. The Uniport, which was built to provide an intuitive interface for soldiers to use as they maneuver through a virtual environment, allows users to control their speed and direction in the virtual environment in a way that is more natural than with a joystick, a mouse, or a keyboard. Also, unlike other interface devices (i.e., joysticks, mice, and keyboards) for virtual environments, the Uniport physically taxes users as they move through the virtual environment (Douglass, Marti, & Jacobsen, 1994).

Description of the Uniport

The Uniport (shown in Figure 1) consists of a unicycle seat mounted on a post in the center of a motor-driven turntable. Pedals attached to the post are used to move forward and backward in the virtual environment. The motor attached to the pedals applies resistance to forward or backward motion that represents the effort required to move through the virtual environment. Pressing on the seat with the thigh rotates the turntable and allows the user to turn left or right in the virtual environment.

As shown in Figure 2, the cables carrying the power and control wires to the motors go through the center of the base plate and the turntable. The cables go part way up the post and then out to the motors. There is no slip ring for the cables; therefore, rotation of the turntable must be limited to prevent the wires from twisting and breaking. The first way rotation is limited is that after a user turns, the turntable rotates back to the zero position. During the return to the zero position, the scene that the user sees does not change, and the return is done at a sub-threshold acceleration so the user does not feel himself or herself moving. The second way rotation is limited is with a mechanical system that physically limits rotation.
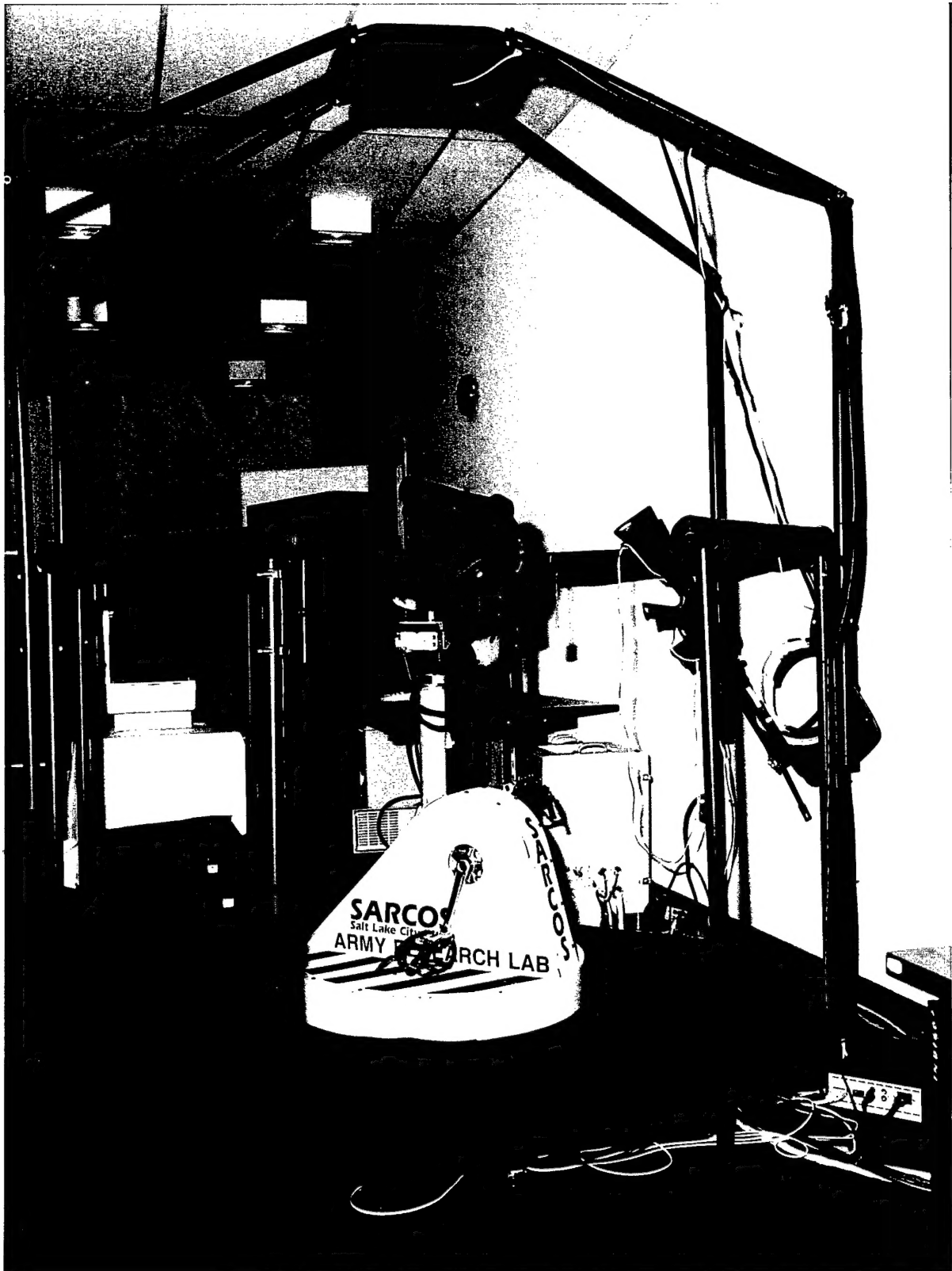
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Figure 1. Uniport.

Figure 2. Uniport with cover removed.

The original mechanical system that limited rotation of the Uniport consisted of a steel cable, one end of which was looped around a pin in the structure between the base plate and the turntable. The other end of the steel cable was looped around a bolt attached to the turntable. As the turntable rotated, the stop cable wrapped around the structure between the turntable and the base plate and stopped the turntable. The stop cable was long enough to allow the Uniport to rotate slightly more than 180° to the left and to the right of its zero position.

Problems With the Means for Limiting Rotation

Although the stop cable system initially performed the function for which it was intended, repeated impact loading of the stop cable caused the bolt holding the end of the stop cable to the turntable to break. It appears that the bolt failed because of fatigue and impact loading. The failure appears to have begun at a thread root. Where the bolt is broken, there is a rough surface typical of a growing fatigue crack and then there is a larger and smoother area which is typical of the sudden fracture that occurs in fatigue failures. The reason that the stresses on the bolt were so high was because the moment arm over which the forces from the stop cable acted was 1.75 inches long. This is a much longer moment arm than was necessary. Appendix A provides an explanation of the force on the bolt generated by the turntable drive motor and the force required to break the bolt.

Another problem with the stop cable system was twisting of the stop cable. Because the stop cable was free to move between the top plate and the turntable, it twisted and kinked. This caused the thimbles on each end of the stop cable to twist, which broke some of the strands of the stop cable.

Rotation of the Uniport at Start

Sometimes when the Uniport is first started, the turntable rotates all the way around until it is stopped by the stop cable. This puts large stresses on the stop cable system because the rotation is very rapid. If the stop cable system fails, the wires going to the turntable and pedal motors could twist and break because the Uniport could continue to rotate. Not only could the system get damaged, but if someone were sitting on the Uniport when it started, he or she could get injured because of the rotation of the Uniport. Clearly, a better means of stopping the turntable from rotating needs to be implemented, and the cause of the rotation of the Uniport at start needs to be discovered and corrected.

Interim Solution for the Stop Cable System

To use the Uniport for research studies and demonstrations while a permanent solution to limit rotation was being designed, another steel stop cable was fabricated. This time, the attachment bolt was shortened so that its moment arm was as short as possible. Also, the stop cable was made without a thimble at the end that attached to the pin in the structure between the base plate and the turntable. By not using a thimble, this end was able to move around the pin more freely, and there was no thimble to twist and break the stop cable.

OBJECTIVE

Design Criteria

The main objective for the Uniport stop system is for it to effectively and reliably stop the turntable from rotating so that the wires going to the motors do not twist and break. There are many other criteria for the design of the stop system. It must be simple, easy to make, easy to install, and have a minimum number of moving parts. It must not require power. It must be quiet and low cost.

DESIGN CALCULATIONS

To meet the design criteria discussed in the Objective, a simple stop plate made from two pieces of steel angle was bolted to the base plate. A stop bolt with a large spacer was attached to the turntable. When the turntable rotates approximately 180° to the left or right of its zero position, the stop bolt hits the stop plate and prevents the turntable from rotating farther in that direction. Figure 3 shows the stop plate and the stop bolt attached to the Uniport.

In designing the stop plate and stop bolt, priority was placed on quickly developing a safe design that would perform reliably. No attempt was made to optimize the design based upon weight or any other criteria. The ability to use available materials was also important. This may have resulted in the over-design of some components, but that trade-off is acceptable. All of the equations used to make calculations for the design of the stop bolt, stop plate, and the bolts holding the stop plate are from the same reference (Shigley, 1977).
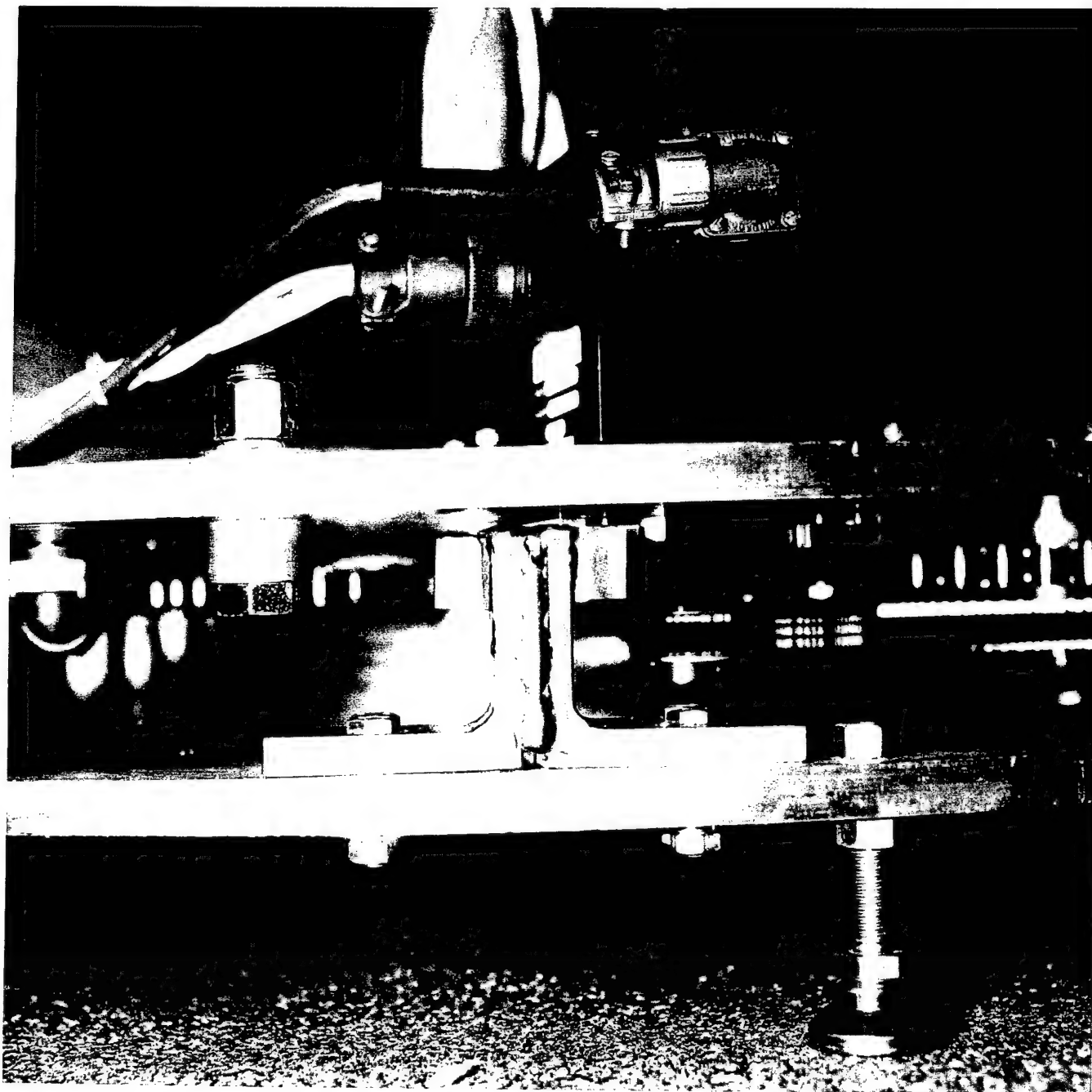
Figure 3. Stop plate and stop bolt.

Torque and Force Generated by the Turntable Motor

The first step in the design is to determine the loads to which the system will be subjected. The motor used to drive the turntable is a Moog 303-030A brushless motor. The continuous stall torque for this motor is 15 lb-in., and the peak stall torque is 60 lb-in. (Moog, Inc., 1995). Figure 4 shows the location of the stop bolt and spacer (6) attached to the turntable.

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It also shows the configuration of the drive motor (2) and the sprockets (3, 4, and 5). For a gear or sprocket, the following equation gives the relationship between applied torque (T) and tangential load (W_t): $T = (d/2)W_t$ in which d is the pitch diameter. Assuming that the torque is equal to the peak stall torque of the turntable drive motor, $T_{a2} = 60$ lb-in. Substituting the sprocket diameters for d and solving for W_t gives the tangential load on the bolt:

$$W_{t6} = 2(d_5/d_6)(d_3/d_4)(T_{a2}/d_2) = 2(12/25.5)(4.5/2)(60/1) = 127 \text{ lb.}$$

As stated by Shigley (1977) on page 606, it is common practice to double the factor of safety when impact is expected. Doubling the load applied to the stop bolt essentially doubles the factor of safety in the design. Therefore, the worst case load on the stop bolt is 254 lb.
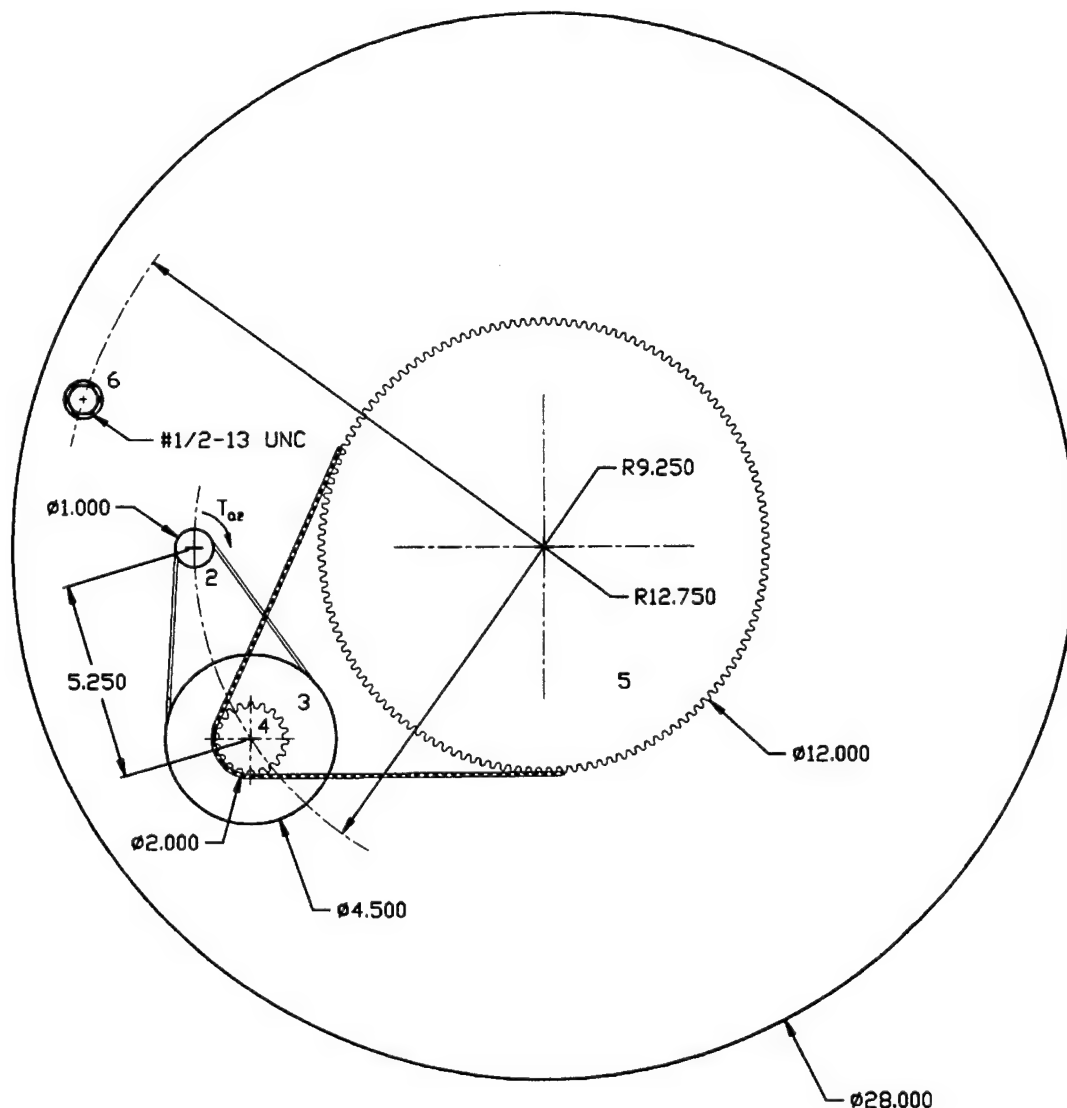

<u>Figure 4.</u> Turntable drive sprockets and stop bolt (dimensions in inches).

Design of the Stop Bolt

There will be a preload on the stop bolt because of the torque used to tighten it. In situations when a bolt is subjected to static loading only, the preload is usually 90% of proof strength. When fatigue loading may be involved, a lower preload is used. The preload for this design will be 50% of the proof strength, and the bolt will be a 1/2-13 unified coarse (UNC), Society for Automotive Engineers (SAE) grade 8 bolt. The equation for preload is $F_i = cS_pA_t$ in which F_i is preload; c is a constant, usually between 0.5 and 0.9, that is chosen based upon the type of loading, static or fatigue; S_p is the proof strength of the bolt; and A_t is the tensile stress area. The preload on the bolt is $F_i = 0.5S_pA_t = 0.5(120,000)(0.0775) = 8,514$ lb. This preload places an initial tensile stress on the bolt. The tensile stress (σ_t) is $\sigma_t = F_i/A_t = 8,514/0.0775 = 60,000$ lb/in^2. Bending stress (σ_b) caused by the impact load is $\sigma_b = Mc/I$ in which the moment (M) is $M = FL = 254(0.375) = 95.25$ lb-in. in which F is the force and L is the length; the distance to the neutral axis (c) is one half of the nominal diameter of the bolt. Therefore, $c = 0.5d = 0.5(0.5) = 0.25$ in., and the area moment of inertia is $I = \pi d^4/64 = \pi(0.5)^4/64 = 0.00307$ in^4. Therefore, $\sigma_b = 95.25(0.25)/0.00307 = 7,762$ lb/in^2. The stress in the y-direction (σ_y) as a result of the tensile stress from the preload and the bending is $\sigma_y = 60,000 + 7,762 = 67,762$ lb/in^2.

Because of friction between the spacer and the top plate, half of the shear force is taken by the top plate. The shear stress (τ_{xy}) on the bolt is then $\tau_{xy} = V/A_r = 127/0.1257 = 1010$ lb/in^2 in which V is the shear force and A_r is the minor diameter area. The principal stresses on the bolt are

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} = \frac{0 + 67,762}{2} \pm \sqrt{\left(\frac{0 - 67,762}{2}\right)^2 + 1010^2}$$

So, $\sigma_1 = 67,777$ lb/in^2 and $\sigma_2 = -15.05$ lb/in^2. The von Mises stress on the stop bolt is $\sigma' = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} = \sqrt{67,777^2 - 67,777(-15.05) + (-15.05)^2} = 67,800$ lb/in^2. By applying the distortion energy theory of failure ($\sigma' = S_y/n$ in which S_y is yield strength and n is the factor of safety) to the load on the bolt, the factor of safety for the design can be determined: $n = S_y/\sigma' = 120,000/67,800 = 1.7$. Therefore, the stop bolt will not fail because of the impact loading.

The next step in the design is to ensure that the stop bolt will not fail because of fatigue loading. To determine the effect of a fluctuating load on the stop bolt, the modified endurance limit (S_e) of the bolt must first be determined. The modified endurance limit is $S_e = k_ak_bk_ck_dk_ek_fS_e'$ in which $S_e' = 0.5S_u = 0.5(150,000) = 75,000$ lb/in^2 in which S_u is the ultimate tensile strength. The surface factor for a machined finish on this bolt is $k_a = 0.71$. Based on the diameter, the size factor is $k_b = 0.85$. The reliability factor for 50% reliability is $k_c = 1$. The temperature factor is $k_d = 1$ because normal operating temperatures will be less than

160° F. The stress concentration factor for rolled threads on an SAE grade 8 bolt is $k_e = 0.333$, and the miscellaneous effects are negligible so that $k_f = 1$. The modified endurance limit for the stop bolt is $S_e = 0.71(0.85)(1)(1)(0.333)(1)(75,000) = 14,200$ lb/in². The fluctuating stresses that could lead to fatigue failure are a result of the impact loading. The alternating stress is $\sigma_a = (\sigma_{max} - \sigma_{min})/2$. The maximum stress ($\sigma_{max}$) is the stress from the preload plus the tensile stress from bending caused by the impact: $\sigma_{max} = 60,000 + 7,762 = 67,762$ lb/in². The minimum stress (σ_{min}) is the stress from the preload minus the compressive stress from bending caused by the impact: $\sigma_{min} = 60,000 - 7,762 = 52,238$ lb/in². So, the alternating stress is $\sigma_a = (67,762 - 52,238)/2 = 7,762$ lb/in². The mean stress (σ_m) is $\sigma_m = (\sigma_{max} + \sigma_{min})/2 = (67,762 + 52,238)/2 = 60,000$ lb/in². The alternating stress and the mean stress are plotted on a fatigue diagram along with a modified Goodman line which goes from S_e to S_u (see Figure 5). The intersection point of the lines going through σ_a and σ_m is below the modified Goodman line. Therefore, the stop bolt will not fail because of fatigue.
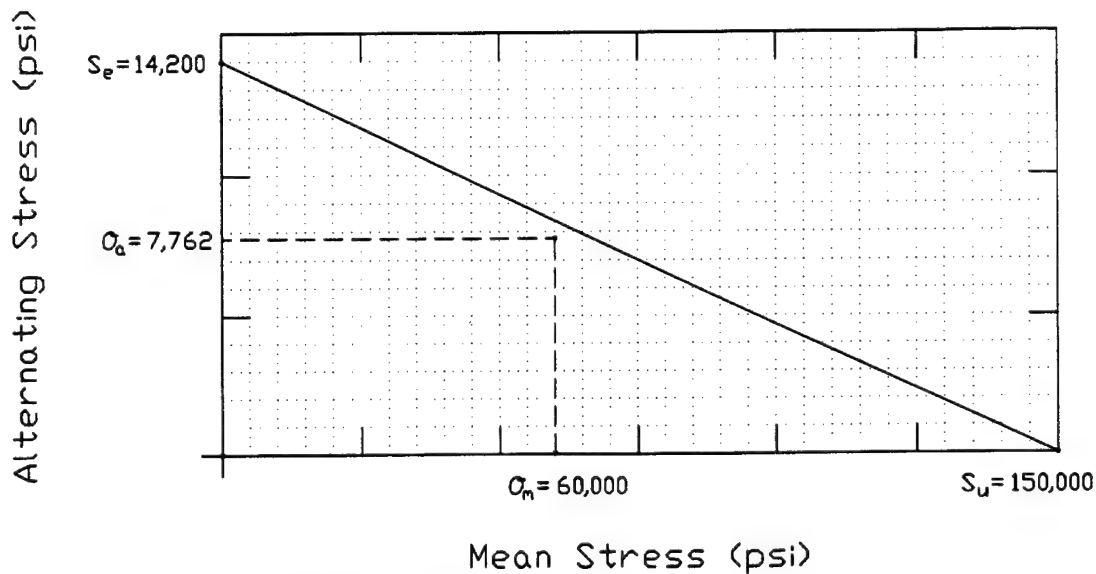
Figure 5. Fatigue diagram for the stop bolt.

Design of the Stop Plate

The stresses (i.e., bending and shear) in the stop plate are caused by the impact loading of the stop bolt. The bending stress is $\sigma_x = Mc/I$. The moment is $M = F L = 254(1.625) = 413$ lb-in. in which F is the impact force and L is the distance from the point of impact to the bend in the angle. The distance to the neutral axis is $c = 0.5t = 0.5(0.75) = 0.375$ in. in which t is the thickness. The area moment of inertia is $I = bh^3/12 = 1.75(.75)^3/12 = 0.0615$ in⁴ in which b is the

width and h is the thickness. So, $\sigma_x = 413(0.375)/0.0615 = 2520$ lb/in^2. The shear stress is τ_{xy} $= V/A = 254/1.75(0.75) = 194$ lb/in^2. The principal stresses are

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} = \frac{2520 + 0}{2} \pm \sqrt{\left(\frac{2520 - 0}{2}\right)^2 + 194^2} ;$$

$$\sigma_1 = 2530 \text{ lb/in}^2 \text{ and } \sigma_2 = -14.8 \text{ lb/in}^2.$$

The von Mises stress is $\sigma' = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} = \sqrt{2530^2 - 2530(-14.8) + (-14.8)^2} = 2540$ lb/in^2. By applying the distortion energy theory of failure, the factor of safety for the stop plate can be determined, $n = S_y/\sigma'$. Because the specifications of the steel angle stocked in the shop are unknown, the yield strength used is that of low strength steel. The factor of safety with respect to impact loading is $n = 26,000/2540 = 10.2$.

Because the loading on the stop plate is completely reversed bending, fatigue failure must be considered in the design. The modified endurance limit of the stop plate is $S_e = k_a k_b k_c k_d k_e k_f S_e'$ in which $S_e' = 0.5 S_u = 0.5(47,000) = 23,500$ lb/in^2 for low strength steel. The surface factor for hot rolled steel is $k_a = 0.7$. Based on the thickness, the size factor is $k_b = 0.85$. The reliability factor for 90% reliability is $k_c = 0.897$. The temperature factor is $k_d = 1$ because normal operating temperatures will be below 160° F. The stress concentration factor is $k_e = 0.667$, and the miscellaneous effects are negligible so that $k_f = 1$. The modified endurance limit for the stop plate is $S_e = 0.7(0.85)(0.897)(1)(0.667)(1)(23,500) = 7,110$ lb/in^2. For completely reversed bending, the alternating stress must be less than the endurance limit. In this design, the alternating stress (i.e., the stress caused by bending, 2,520 lb/in^2) is less than the modified endurance limit (7,110 lb/in^2). Therefore, the factor of safety with respect to fatigue is $n = S_e/\sigma_a$ $= 7,110/2,520 = 2.8$.

Design of the Means to Attach the Stop Plate

The stop plate will be attached to the Uniport base plate with four 1/4-20 UNC, SAE grade 3 bolts. The bolts will be evenly spaced, two on each half of the stop plate. Like the stop bolt, these bolts will have a preload put on them when they are tightened. The preload will be 60% of proof strength, $F_i = 0.6 S_p A_t = 0.6(85,000)(0.0318) = 1,621.8$ lb. The tensile stress caused by the preload is $\sigma = F_i/A_t = 1,621.8/0.0318 = 51,000$ lb/in^2. Because of friction between the stop plate and the base plate, the shear force on the bolts is 127 lb. The shear stress on each bolt is $\tau_{xy} = V/4A_r = 127/4(0.0269) = 1,180$ lb/in^2.

The bolts must resist the moment put on the stop plate when it is hit by the stop bolt. In the section about the stop plate design, the moment was determined to be 413 lb-in. Because the bolts compress the steel stop plate and the aluminum (Al) base plate, the stiffness of each must be considered when determining the stress on the bolts during the impact loading. The stiffness of the bolt (k_b) is $k_b = \pi d^2 E/4l = \pi(0.25)^2(30*10^6)/4(0.5+0.375) = 1.68*10^6$ lb/in. in which d is the nominal diameter, E is the elastic modulus, and l is the thickness of the stop plate and the base plate. The stiffness of the members (k_m) is $1/k_m = 1/k_{steel}+1/k_{Al}$ in which $k_{steel} = 2\pi d^2 E/l = 2\pi(0.25)^2(30*10^6)/0.375 = 31.4*10^6$ lb/in. and $k_{Al} = 2\pi d^2 E/l = 2\pi(0.25)^2(10.3*10^6)/0.5 = 8.09*10^6$ lb/in. Now, $1/k_m = 1/31.4*10^6+1/8.09*10^6 = 1.555*10^{-7}$, and $k_m = 1/1.555*10^{-7} = 6.43*10^6$ lb/in. The load (P) required to counter the moment (M) is $P = M/l = 413/1.5 = 275$ lb in which l is the length from the bolt hole to the mid point of the stop plate. For a single bolt $P = 275/2 = 138$ lb. The force on the bolt (F_b) is $F_b = [k_b P/(k_b+k_m)]+F_i = [1.68*10^6(138)/(1.68*10^6+6.43*10^6)]+1621.8 = 1650$ lb. The tensile stress on the bolt is then $\sigma_y = F_b/A_t = 1,650.8/0.0318 = 51,900$ lb/in^2. The principal stresses are

$$\sigma_1,\sigma_2 = \frac{\sigma_x+\sigma_y}{2}\pm\sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2+\tau_{xy}^2} = \frac{0+51,900}{2}\pm\sqrt{\left(\frac{0-51,900}{2}\right)^2+1,180^2} \ ;$$

$$\sigma_1 = 51,900 \text{ lb/in}^2 \text{ and } \sigma_2 = -26.8 \text{ lb/in}^2.$$

The von Mises stress is

$$\sigma' = \sqrt{\sigma_1^2-\sigma_1\sigma_2+\sigma_2^2} = \sqrt{51,900^2-51,900(-26.8)+(-26.8)^2} = 51,900 \text{ lb/in}^2.$$

According to the distortion energy theory of failure, if the von Mises stress exceeds the yield strength of the material (85,000 lb/in^2 for one of these bolts), the item will fail. In this case, the yield strength is not exceeded, and the factor of safety for this design is $n = S_y/\sigma' = 85,000/51,900 = 1.6$.

To determine whether the bolts will fail because of fatigue, the alternating stress and the mean stress need to be determined. The alternating stress is

$$\sigma_a = \frac{Pk_b}{2A_t(k_b+k_m)} = \frac{138(1.68*10^6)}{2(0.0318)(1.68*10^6+6.43*10^6)} = 449 \text{ lb/in}^2.$$

The mean stress is $\sigma_m = \sigma_a+F_i/A_t = 449+1,621.8/0.0318 = 51,449$ lb/in^2. The modified endurance limit for the bolts is $S_e=k_a k_b k_c k_d k_e k_f S_e'$ in which $S_e' = 0.5S_u = 0.5(110,000) = 55,000$ lb/in^2. The surface factor for a machined finish on this bolt is $k_a = 0.74$. Based on the diameter, the size factor is $k_b = 1$. The reliability factor for 90% reliability is $k_c = 0.897$. The temperature factor is $k_d = 1$ because normal operating temperatures will be below 160° F. The

stress concentration factor is $k_e = 0.333$ for rolled threads on grade 3 bolts, and the miscellaneous effects are negligible so that $k_f = 1$. The modified endurance limit for the stop plate is $S_e = 0.74(1)(0.897)(1)(0.333)(1)(55,000) = 12,200$ lb/in^2. In Figure 6, the alternating stress and the mean stress are plotted on a fatigue diagram along with a modified Goodman line. The intersection of the lines going through σ_a and σ_m is below the modified Goodman line. Therefore, the bolts will not fail because of fatigue.
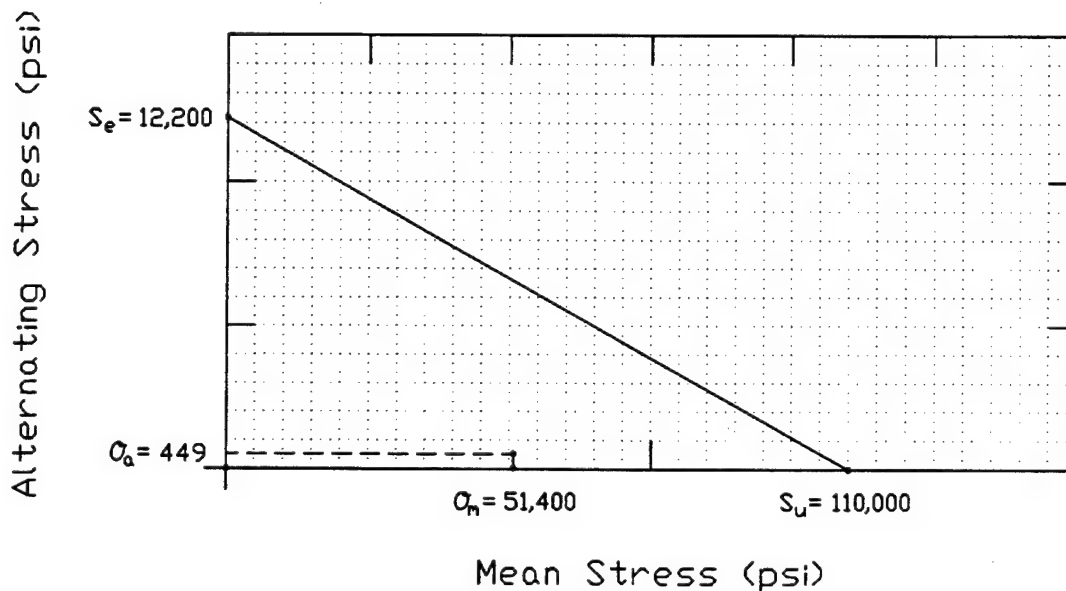

Figure 6. Fatigue diagram for the bolts holding the stop plate.

FABRICATION AND INSTALLATION

The stop plate was fabricated from two pieces of steel angle according to the drawing shown in Figure 7. To ensure that the bolt heads were seated flush on the steel angles, the areas around the bolt holes were spot faced. The edge welds were used to ensure that the two pieces acted as one unit and did not separate as a result of the impact loading. The edge welds also made positioning of the stop plate for installation easier.
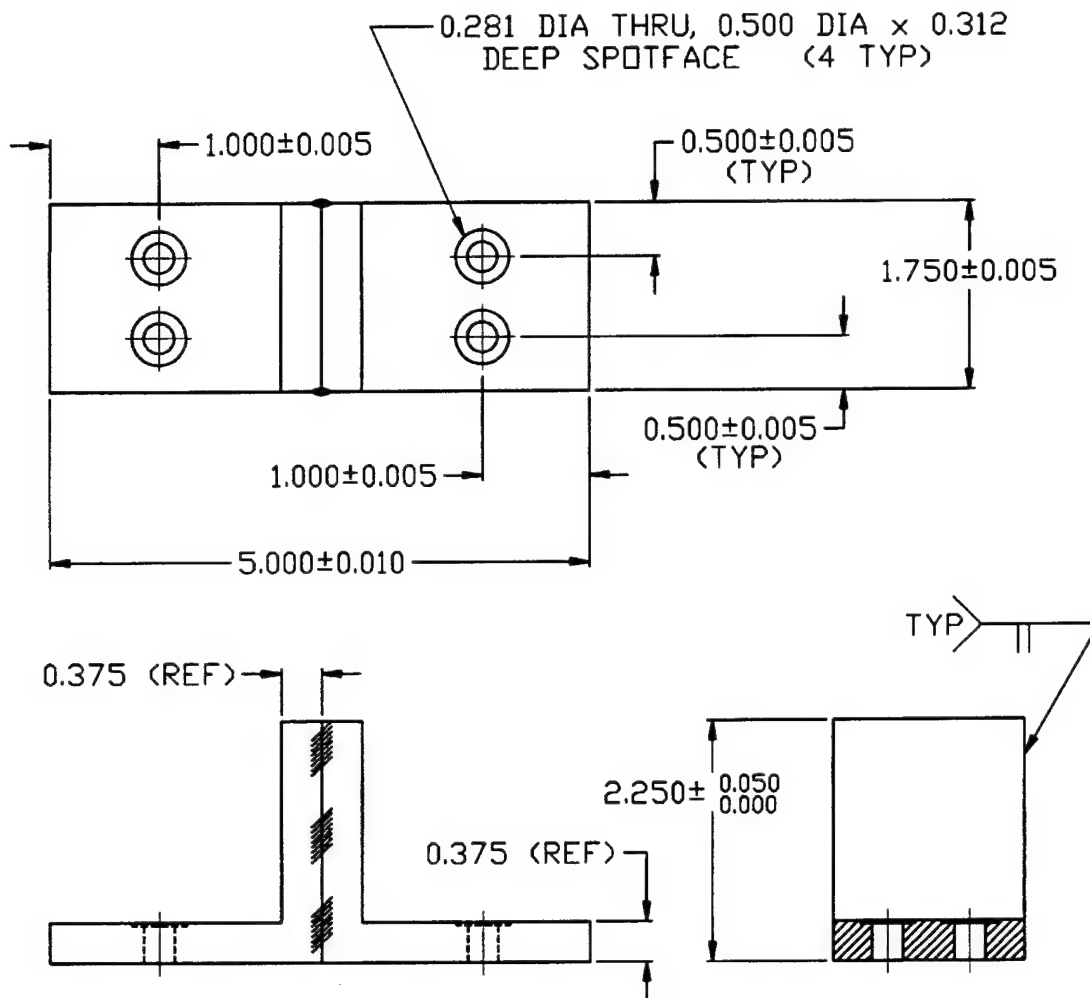
Figure 7. Stop plate (dimensions in inches).

The first part to be installed was the stop plate. It was clamped on the bottom of the base plate 0.375 inch from the edge. Then it was used as a guide for drilling the mounting holes. The clamps were removed and two strips of Sorbothane® 0.5 inch thick were attached to the part of the stop plate where the stop bolt would impact. The Sorbothane, which was attached with cyanoacrylate adhesive, was used to deaden the sound and to reduce the impact when the stop bolt hit the stop plate. Sorbothane is a viscoelastic polymer designed to reduce impact and vibration. Then the stop plate was bolted in place on the top of the base plate. Washers and lock washers were used under each nut to prevent loosening. The mounting bolts were torqued to 81 lb-in. Next, a hole for the stop bolt was drilled through the turntable 180° from the stop plate when the Uniport was at the zero position. A washer and a lock washer were used to prevent loosening. The stop bolt was torqued to 851 lb-in.

OPERATION AND PERIODIC INSPECTIONS

The stop plate and stop bolt have been designed to withstand impact and fatigue loading expected during normal use. This will prevent the system from spinning around at start and over-twisting the wires that control the pedal motor and the turntable motor. The limitation on turning will also prevent users from over-twisting the wires. Although turning is limited to slightly less than 180° in each direction from the zero point, this should be sufficient for most motions that a user would want to make in a virtual environment with the Uniport. Since they were installed 16 July 1996, the stop plate and stop bolt have worked several times to stop the Uniport from rotating too far.

To ensure the continued safety and reliability of the Uniport, the stop plate and stop bolt should be inspected periodically. During the inspection, the Sorbothane should be examined for damage and replaced if necessary. The stop bolt and the bolts holding the stop plate should be checked for looseness and re-tightened to torques of 851 and 81 lb-in., respectively. Initially, the periodic inspections should be done at 6-month intervals. If no damage to the Sorbothane is noticed and none of the bolts need to be re-tightened during the first three inspections, then inspections can be scheduled annually.

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APPENDIX A

FORCES ON THE STOP CABLE SYSTEM

FORCES ON THE STOP CABLE SYSTEM

To determine the forces on the bolt attaching the stop cable to the turntable, the forces generated by the drive motor must be determined. The location of the bolt (6) to hold the stop cable, the location of the drive motor (2), and the arrangement of the sprockets (3,4, and 5) that drive the turntable are shown in Figure A-1. For gears and sprockets, the relationship between torque (T) and tangential force (W_t) is $T = (d/2)W_t$ in which d is the pitch diameter. Assuming that the torque is equal to the continuous stall torque of the turntable drive motor, $T_{a2} = 15$ lb-in. (Moog, 1995). Substituting the sprocket diameters for d and solving for W_t gives $W_{t6} = 2(d_5/d_6)(d_3/d_4)(T_{a2}/d_2) = 2(12/20.5)(4.5/2)(15/1) = 39.5$ lb. This is the force in the tangential direction. The angle that the stop cable makes with the structure around which it wraps is approximately 22.5°. Therefore, the maximum resultant force (R) on the bolt is $R = 39.5/\sin 22.5° = 103$ lb, assuming that the drive motor torque is 15 lb-in.

Although the drive motor can impart 103 lb of force to the bolt holding the stop cable, only 30.2 lb of force are required to cause a fatigue failure of the bolt holding the stop cable to the turntable. Figure A-2 shows a cross-sectional view of the bolt holding the stop cable to the turntable. (Note the distance between the stop cable and the nut holding the bolt to the turntable.) The bending stress in the bolt is $\sigma_y = Mc/I$. The moment (M) is $M = FL$ in which F is the applied force, and L is the length of the moment arm. The distance to the neutral axis is c, and the area moment of inertia is $I = \pi d^4/64$ in which d is the minor diameter. So, $\sigma_y = FLc/(\pi d^4/64) = F(1.8125)(0.1469)/[\pi(0.2938)^4/64] = 728F$ lb/in^2. For fatigue failure, the modified endurance limit (S_e) of the bolt is found from the equation $S_e = k_a k_b k_c k_d k_e k_f S_e'$. For an SAE grade 5 bolt, $S_e' = 0.5 S_u = 0.5(120,000) = 60,000$ lb/in^2 in which S_u is the ultimate tensile strength. The surface factor for a machined finish on this bolt is $k_a = 0.71$. Based on the diameter, the size factor is $k_b = 0.85$. The reliability factor for 50% reliability is $k_c = 1$. The temperature factor is $k_d = 1$ because normal operating temperature was below 160° F. The stress concentration factor is $k_e = 0.333$ for rolled threads on grade 3 to grade 8 bolts, and the miscellaneous effects are negligible so that $k_f = 1$. The modified endurance limit for the stop plate is $S_e = 0.71(0.85)(1)(1)(0.333)(1)(60,000) = 12,100$ lb/in^2.
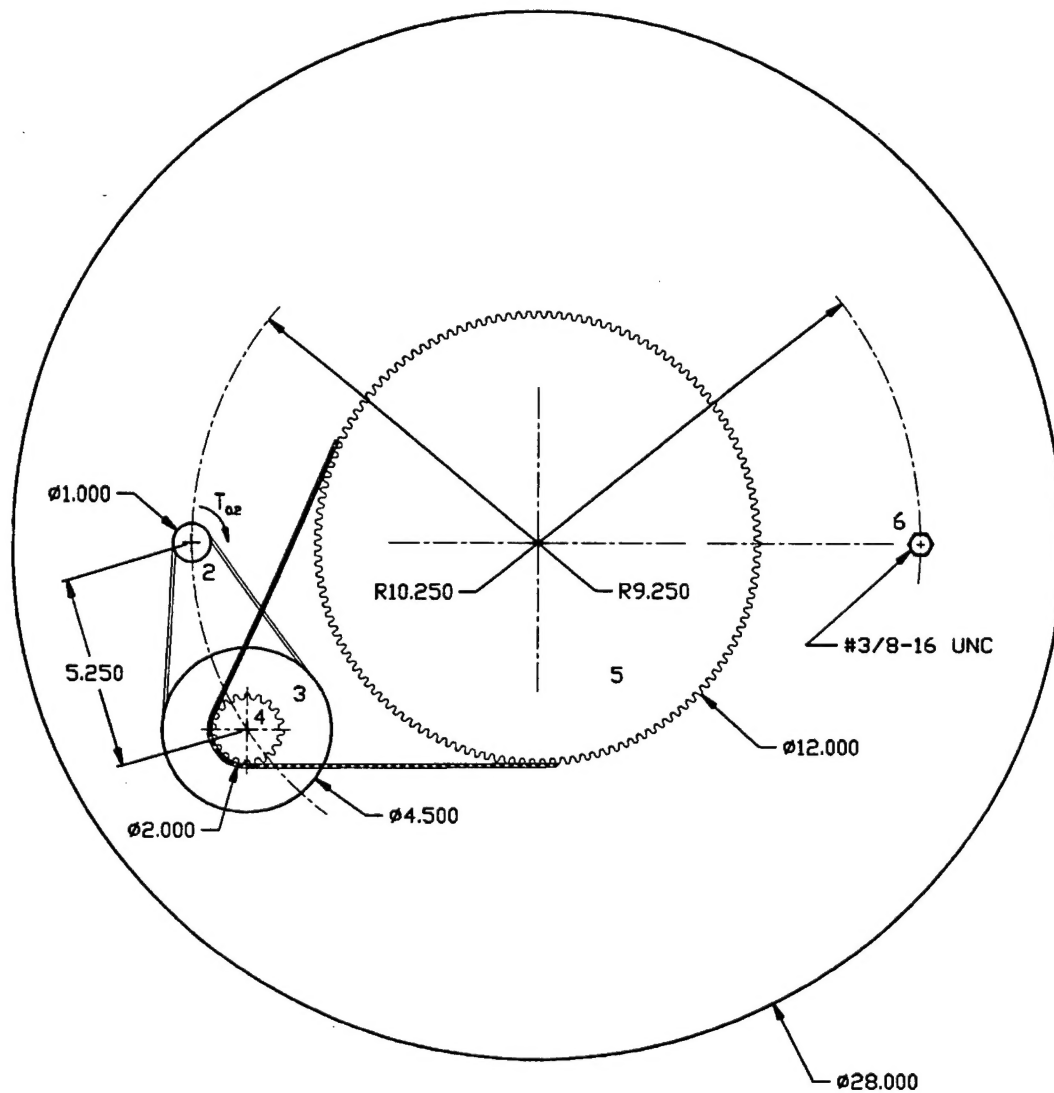
Figure A-1. Turntable drive sprockets and bolt holding stop cable (dimensions in inches).

The alternating stress is $\sigma_a = (\sigma_{max} - \sigma_{min})/2 = (728F-0)/2 = 364F$ lb/in^2, and the mean stress is $\sigma_m = (\sigma_{max} + \sigma_{min})/2 = (728F+0)/2 = 364F$ lb/in^2. The values of σ_a and σ_m are used to determine a line having a slope of σ_a/σ_m and going through the origin of a fatigue diagram. The intersection of that line and the line going through S_e and S_u determines the alternating stress at which fatigue failure will occur. (See the fatigue diagram in Figure A-3.) The force required for fatigue failure to occur is determined by the equation $\sigma_a = S_a$. Therefore, for $\sigma_a = 364F$ and $S_a = 11,000$ lb/in^2, the force on the bolt (with such a long moment arm) that will cause fatigue failure is $F = 11,000/364 = 30.2$ lb.

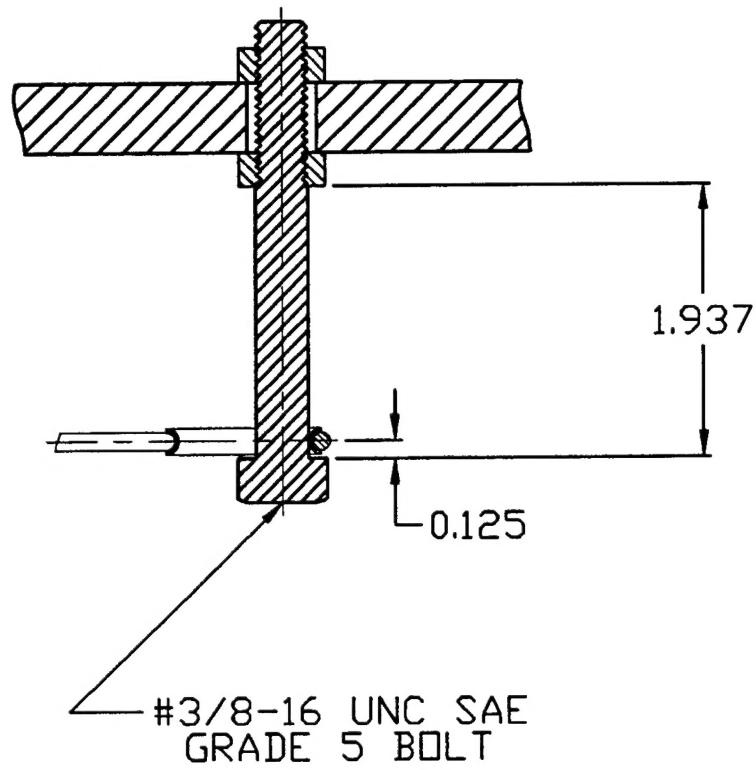Figure A-2. Bolt holding stop cable to turntable (dimensions in inches).

1.937

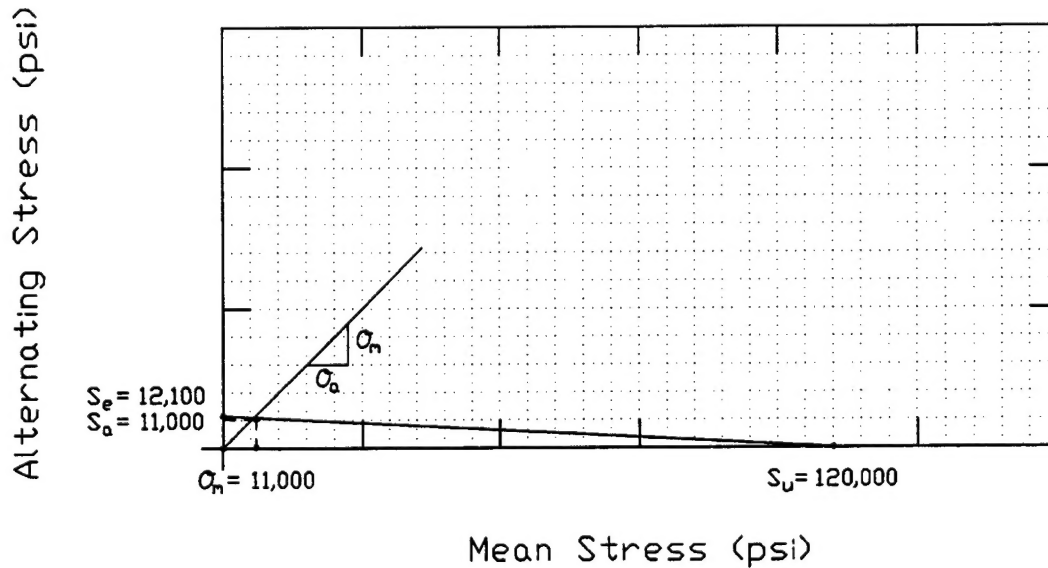0.125

#3/8-16 UNC SAE
GRADE 5 BOLT

Figure A-3. Fatigue diagram for the bolt holding the stop cable.

S_e = 12,100
S_a = 11,000

σ_m = 11,000

S_u = 120,000

σ_m

σ_a

Alternating Stress (psi)

Mean Stress (psi)

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13. ABSTRACT *(Maximum 200 words)*

This report has two main purposes. The first is to document the problems with the previous system for limiting rotation of the Uniport. The second purpose is to document the design of the new system to limit rotation of the Uniport. (The Uniport consists of a unicycle type mobility platform, which allows a person to "pedal" his or her way through the virtual environment.) The previous system for limiting rotation consisted of a steel cable attached to a support structure at one end and bolted to the turntable at the other end. This system suffered from two main problems. The moment arm for the bolt holding the cable was so long that it created large stresses in the bolt, which caused it to fail by fatigue. The other main problem was that the cable twisted and kinked, which caused some of the strands of the cable to break. The new system for limiting rotation has been designed to resist fatigue failure and failure from impact loading. The stop plate and stop bolt provide an effective and reliable means to limit rotation of the Uniport.

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